

# A simple varying-speed-of-light hypothesis is enough for explaining high-redshift supernovae data

Yves-Henri Sanejouand

Laboratoire de Physique, UMR 5672 du CNRS,  
Ecole Normale Supérieure de Lyon,  
46 allées d'Italie, 69364 Lyon Cedex 07, France.  
Yves-Henri.Sanejouand@ens-lyon.fr

## Abstract

The hypothesis that the speed of light decreases by nearly  $2 \text{ cm s}^{-1}$  per year is discussed within the frame of a simple phenomenological model. It is shown that this hypothesis can provide an alternative explanation for the redshift-distance relationship of type Ia supernovae, which is nowadays given in terms of a new form of (dark) energy of unknown origin.

Keywords: cosmological constant; fine-structure constant; Hubble law; lunar ranging laser data; vacuum permittivity and permeability.

## 1 Introduction

Supernovae can be used as standard candles for cosmological measurements, especially those belonging to the rather homogeneous type Ia subclass (Sne Ia). In 1998, studies of high-redshift Sne Ia provided strong evidences for an acceleration of the universe's expansion[1, 2], instead of the expected deceleration (due to gravitational forces). A non-zero cosmological constant (a "dark energy" with negative pressure) can explain such results[1, 2], but because this explanation bears greatly on "new physics"[3] and involves a "cosmic coincidence"[4, 5], alternative ones have to be explored. For instance, from an epistemological point of view, a non-zero cosmological constant would mean that laws of physics at cosmological scales are different from what can be observed on earth, breaking down one of the major principle followed by physicists with so many successes over centuries.

The purpose of this paper is to show that high-redshift supernovae data are consistent with the hypothesis that the speed of light is time-dependent. Such an hypothesis was already proposed during the thirties, for explaining the cosmological redshift[6, 7, 8]. It has been reconsidered more recently[9],

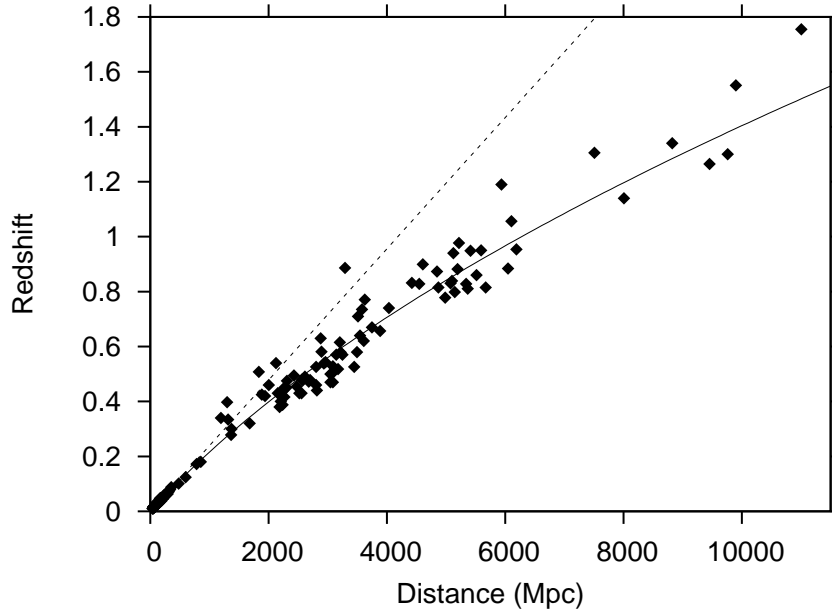


Figure 1: Redshift of type Ia supernovae as a function of their distance. Black diamonds: the 156 supernovae of the recently compiled "gold set". Dotted line: Hubble law. Plain line: the relationship expected according to the varying-speed-of-light hypothesis discussed in the present study. This is *not* a fit of the data. The distance scale is set using a value for the Hubble constant of  $72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

noteworthy within the frame of standard cosmological models, although not on the same timescale[10, 11]; for a discussion of the status of present varying-speed-of-light theories, see Ref. [12].

## 2 Redshift-distance relationship

Light curves of distant Sne Ia are dilatated in time[13, 14], according to:

$$\frac{T_d}{T_0} = 1 + z \quad (1)$$

where  $T_0$  and  $T_d$  are the typical timescales of the event, as observed in the case of nearby and distant Sne Ia, respectively,  $z$  being the redshift of the distant supernova. As a matter of fact, a stretching by a  $(1 + z)$  factor of reference, nearby, Sne Ia light curves is included in all analyses of distant Sne Ia data[13, 14].

Within the frame of standard cosmological models, (1) is understood through the hypothesis that the corresponding length ( $c_0 T_0$ ) increases as a function

of time,  $c_0$ , the speed of light, being assumed to have the same, time-independent, value, as measured on earth[15, 16]. Let us assume instead that (1) reflects the fact that the speed of light is time-dependent, so that:

$$\frac{c_d}{c_0} = 1 + z \quad (2)$$

where  $c_d$  is the speed of light at time  $t_d$ , when the photons were emitted. Indeed, a relationship between a timescale measured by an observer and the speed of light at the time it was emitted, so that  $T_d \propto c_d$  can be obtained in the context of non-relativistic models (see Ref. [7], as an early example). Hereafter, for the sake of clarity, the chosen point of view is also non-relativistic. However, note that an effective variation of the speed of light, as a consequence of a variation of the gravitational field, can also be obtained within the frame of General Relativity[6, 12].

If the speed of light varies slowly as a function of time,  $c_d$  can be approximated by:

$$c_d = c_0 + a_c \Delta t + \frac{1}{2} \dot{a}_c \Delta t^2 + \dots$$

where  $a_c$  is the time derivative of the speed of light,  $\dot{a}_c$  the time derivative of  $a_c$ , and where  $\Delta t$  is the photon time-of-flight between its source and the observer. Let us consider only the first terms of this expansion, namely, that for small enough values of  $\Delta t$ :

$$c_d = c_0 + a_c \Delta t \quad (3)$$

During  $\Delta t$ , the photon travels along a path of length  $d$ , so that:

$$d = c_0 \Delta t + \frac{1}{2} a_c \Delta t^2$$

This yields:

$$\Delta t = \frac{c_0}{a_c} \left( \sqrt{1 + \frac{2a_c d}{c_0^2}} - 1 \right) \quad (4)$$

Thus, with (3):

$$c_d = c_0 \sqrt{1 + \frac{2a_c d}{c_0^2}} \quad (5)$$

and, with (5) in (2):

$$z = \sqrt{1 + \frac{2a_c d}{c_0^2}} - 1 \quad (6)$$

For short distances, (6) can be approximated by:

$$z = \frac{a_c d}{c_0^2} \quad (7)$$

a relationship of the same form as Hubble law, namely:

$$z = \frac{H_0 d}{c_0} \quad (8)$$

where  $H_0$  is the Hubble constant. So, with (7) and (8):

$$a_c = H_0 c_0 \quad (9)$$

and (6) becomes:

$$z = \sqrt{1 + \frac{2H_0 d}{c_0}} - 1 \quad (10)$$

Note that (10) can also be viewed as a straightforward generalisation of Hubble law. Indeed, rewriting (8) as  $z = H_0 \Delta t$ , (10) is then obtained from (4) and (9). In other words, (10) is a modified version of Hubble law where  $\Delta t$ , the photon time-of-flight, is calculated so as to take into account the time-dependence of the speed of light.

Interestingly, (9) has already been obtained in other contexts. First, as the critical value for the acceleration below which Newton laws are no longer valid, according to the MOND alternative explanation of the dark matter problem[17]. Then, as the value of an anomalous, unexplained, acceleration directed towards the sun, that has been found to act on distant spacecrafts in the solar system, noteworthy Pioneer 10 and 11, launched some thirty years ago[18, 19].

### 3 Data

The 156 supernovae considered in this study are those taken into account within the frame of an analysis of 16 high-redshift supernovae observed with the Hubble Space Telescope; see Table 5 in Ref. [20]. This "gold set" has the virtue that all distance estimates were derived from a single set of algorithms[20]. In order to check (10) against these experimental data, magnitudes were first translated into actual distances, as it is legitimate to do in the case of standard candles. However, assuming a given value for  $H_0$  is still necessary due of the lack of enough reliable data in the case of nearby Sne Ia.

### 4 Results

In Figure 1, Sne Ia redshifts are plotted as a function of their distance. The plain line is *not* a least-square fit of these data. It corresponds to (10), that is, to the hypothesis that Sne Ia redshifts are observed as a consequence of the time-dependence of the speed of light. More specifically, according to (9), if  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [21], then  $a_c = 7 \cdot 10^{-10} \text{ m s}^{-2}$ . This corresponds to a change in the speed of light of  $-2.2 \text{ cm s}^{-1}$  per year.

## 5 Discussion

### 5.1 Fine-structure constant

Given the central role of the speed of light in modern theoretical physics, consequences of its variation, even at slow rate, are far reaching. But from an experimental point of view the major constraint comes from the fact that  $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c_0}$ , the fine-structure constant, depends very little upon the redshift[22], if it does at all[23, 24]. This means that if the speed of light varies in time as much as assumed herein, then either  $\epsilon_0$ , the vacuum permittivity,  $e$ , the electron charge,  $\hbar$ , the Planck constant, or both, vary as well. However, because there is a known link between  $c_0$  and  $\epsilon_0$ , namely:

$$c_0 = \frac{1}{\sqrt{\mu_0\epsilon_0}} \quad (11)$$

where  $\mu_0$  is the vacuum permeability, the simplest hypothesis is to assume that the vacuum permittivity also varies in time, so that:

$$\epsilon(t)c(t) = \frac{e^2}{4\pi\hbar\alpha} \quad (12)$$

does not. Moreover, (11) and (12) are consistent only if the vacuum permeability also varies in time, so that:

$$\mu(t) = \frac{(4\pi\hbar\alpha)^2}{e^4}\epsilon(t)$$

In other words, if the speed of light varies in time, while the fine-structure constant does not, then the ratio between vacuum permittivity and permeability also does not. However, building a self-consistent theory of the relationship between light, matter and vacuum properties, as done for instance in another context in Ref. [11], is beyond the scope of this study. As a matter of fact, such a kind of work may await confirmation at the experimental level, as well as further clues, in order to be developed on firm enough grounds.

### 5.2 Physical units

In the present international unit system, the value of  $c_0$  is exactly 299,792,458 m s<sup>-1</sup>, *par définition*. But because  $c_0$  is involved in other physical units, variations of some of the corresponding physical constants should reflect any actual time-dependence of the speed of light. However, most physical constants are known with a relative standard uncertainty of 10<sup>-9</sup>, according to the 2002 CODATA set of recommended values. This is likely to be not yet enough for demonstrating a relative variation of 10<sup>-10</sup> per year, as expected herein for the speed of light.

### 5.3 Lunar laser ranging

Distances in the Solar system can be measured using radar or laser impulses, the Earth-Moon distance being the most accurately determined one[25]. So, if the speed of light varies in time, a systematic trend should be observed in these distance measurements. Indeed, such a trend has been obtained by laser ranging. It corresponds to a rate of change of the measured Earth-Moon distance of  $3.82 \pm 0.07$  cm per year[25]. These distance time series,  $d_{mes}(t)$ , are obtained assuming that:

$$d_{mes}(t) = \frac{c_0 \delta t}{2} \quad (13)$$

where  $\delta t$  is the time taken by light to go to the Moon and back to the observer. If the speed of light varies in time,  $\delta t$  is approximatively given by:  $\delta t = \frac{2d_0}{c(t)}$ , where  $d_0$  is the actual Earth-Moon distance, that is, with (13):

$$d_{mes}(t) = \frac{c_0}{c(t)} d_0$$

According to the present study,  $c(t)$  is given by (3), with  $t = 0$  when the first distance measurements were performed. Taking into account (9) yields:

$$d_{mes}(t) = \frac{d_0}{1 - H_0 t}$$

So, as a consequence of the variation of the speed of light, the rate of change of the measured Earth-Moon distance,  $v_{mes}$ , is expected to be, for short periods of measurements (accurate measurements of the Earth-Moon distance have been performed over the last thirty years, after reflectors were let on the Moon by Apollo missions):

$$v_{mes} = H_0 d_0$$

that is, a Hubble-like relationship. In other words, according to the present study, distances in the solar system should seem to increase in time, as if the solar system were expanding at the rate of universe's expansion. So, depending upon the actual value of  $H_0$ , part or all the lunar recession measured by laser ranging could be due to the time-dependence of the speed of light. In particular, if  $H_0 = 97 \text{ km s}^{-1} \text{ Mpc}^{-1}$  it is an apparent effect.

On the other hand if  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [21], the pseudo-lunar recession due to the variation of the speed of light is of 2.8 cm per year. The nearly 1 cm per year difference could come from an actual lunar recession, as a consequence of tidal forces. Such forces are also expected to be responsible for a secular change in the length of the day (LOD). In a remarkable compilation of ancient eclipses[26], it was shown that the mean LOD change has been of  $+1.70 \pm 0.05$  milliseconds per century over the last 2500 years.

Under the hypotheses that the momentum of the Moon-Earth system is conserved and that, during this period, all the LOD change was due to tidal forces, the tidally-driven lunar recession should have been of nearly 2.8 cm per year[26], leaving a value for the pseudo-lunar recession of only 1 cm per year. However, significant LOD fluctuations are observed in the ancient eclipses data, on the millenium timescale[26], while fluctuations of several milliseconds have been observed over the last centuries, likely to be due to events like the warm El Nino Southern Oscillation, which is accompanied by an excess in atmospheric angular momentum[27]. As a matter of fact, between 1969 and 2005, that is, while the lunar laser ranging data were collected, the mean LOD has decreased.

## 6 Conclusion

From a theoretical point of view, the varying-speed-of-light hypothesis discussed in this study is challenging. However, because it is consistent with experimental data, and especially because it explains the supernovae data so well, it should prove useful, at least at an heuristic level. From an experimental point of view, measuring the speed of light with a  $\text{cm s}^{-1}$  accuracy several years in a row may not be out of reach. However, measuring its variations at this level of accuracy should prove easier.

## References

- [1] A. Riess, A. Filippenko, P. Challis, A. Clocchiatti, A. Diercks, P. Garnavich, R. Gilliland, C. Hogan, S. Jha, R. Kirshner, B. Leibundgut, M. Phillips, D. Reiss, B. Schmidt, R. Schommer, R. Smith, J. Spyromilio, C. Stubbs, N. Suntzeff, J. Tonry, *AJ* **116**, 1009 (1998).
- [2] R. Quimby, C. Lidman, R. Ellis, M. Irwin, R. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B. Boyle, A. Filippenko, *Ap. J.* **517**, 565 (1999).
- [3] P. J. E. Peebles, B. Ratra, *Rev. Mod. Phys.* **75**, 559 (2003).
- [4] I. Zlatev, L. Wang, P. J. Steinhardt, *Phys. Rev. Lett.* **82**, 2858 (1999).
- [5] V. Sahni, *Class. Quantum Grav.* **19**, 3435 (2002).
- [6] T. Takehuchi, *Zeits. Phys.* **69**, 857 (1931).
- [7] P. Wold, *Phys. Rev. E* **47**, 217 (1935).
- [8] J. North, *The measure of the universe. A History of modern cosmology*, (Oxford University Press, 1965).

- [9] A. Giere, A. Tan, *Chin. J. Phys.* **24**, 217 (1986).
- [10] J. Barrow, J. Magueijo, *ApJ* **532**, L87 (2000).
- [11] A. Ranada, *Europhys. letters* **61**, 174 (2003).
- [12] J. Magueijo, *Rep. Progr. Phys.* **66**, 2025 (2003).
- [13] M. Kim, J. Lee, T. Matheson, R. McMahon, H. Newberg, R. Pain, *Nucl. Phys. B* **51**, 123 (1996).
- [14] B. Leibundgut, R. Schommer, M. Phillips, A. Riess, B. Schmidt, J. Spyromilio, J. Walsh, N. Suntzeff, M. Hamuy, J. Maza, R. Kirshner, P. Challis, P. Garnavich, R. Smith, A. Dressler, R. Ciardullo, *ApJ* **466**, L21 (1996).
- [15] E. Schrodinger, *Physica* **6**, 899 (1939).
- [16] O. Wilson, *ApJ* **90**, 634 (1939).
- [17] M. Milgrom, *ApJ* **270**, 365 (1983).
- [18] J. Anderson, P. Laing, E. Lau, A. Liu, M. Nieto, S. Turyshev, *Phys. Rev. Lett.* **81**, 2858 (1998).
- [19] J. Anderson, P. Laing, E. Lau, A. Liu, M. Nieto, S. Turyshev, *Phys. Rev. D.* **65**, 082004 (2002).
- [20] A. Riess, L. Strolger, J. Tonry, S. Casertano, H. Ferguson, B. Mobasher, P. Challis, A. Filippenko, S. Jha, W. Li, R. Chornock, R. Kirshner, B. Leibundgut, M. Dickinson, M. Livio, M. Giavalisco, C. Steidel, T. Benitez, Z. Tsvetanov, *ApJ* **607**, 655 (2004).
- [21] W. Freedman, B. Madore, B. Gibson, L. Ferrarese, D. Kelson, S. Sakai, J. Mould, R. Kennicutt, H. Ford, J. Graham, J. Huchra, S. Hughes, G. Illingworth, L. Macri, P. Stetson, *ApJ* **553**, 47 (2001).
- [22] J. Webb, V. Flambaum, C. Churchill, M. Drinkwater, J. Barrow, *Phys. Rev. Lett.* **82**, 884 (1999).
- [23] J.-P. Uzan, *Rev. Mod. Phys.* **75**, 403 (2003).
- [24] H. Chand, R. Srianand, P. Petitjean, B. Aracil, *A&A* **417**, 853 (2004).
- [25] J. Dickey, P. Bender, J. Faller, X. Newhall, R. Ricklefs, J. Riesi, P. Shelus, C. Veillet, A. Whipple, J. Wiant, J. Williams, C. Yoder, *Science* **265**, 482 (1994).
- [26] F. Stephenson, L. Morrison, *Philos. Trans. R. Soc. London A* **351**, 165 (1995).
- [27] W. Munk, *Proc. Natl. Acad. Sci. USA* **99**, 6550 (2002).